



Embedded Thermal Control Subsystems for Next Generation Spacecraft Applications

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Technical Overview

Embedded Thermal Control with Intelligent Capabilities

- **Technical Challenges & Applications**
 - **Silicon Based Thermal Management: High Heat Flux Acquisition**
 - **Multi-functional Structures: Embedded Electrohydrodynamic (EHD) Based Pumps for structural-thermal plates**
- **Develop Proof of Concept Hardware**
 - **STP-H5 ISEM: EHD Plate Experiment**
 - **Component Level Heat Acquisition (Chip Integrated – Thermal Management System)**





Technical Overview

- **Fundamental Research:**
 - *Electrically Driven Liquid Film Boiling* NASA HQ SLPSRA Division NNX12AR32G (Yagoobi/WPI & Didion)
 - *Self-Sensing Thermal Management Using nano-enhanced Polymers* NSTRF FY13 (Bruck & Sauerbrunn/UMD & Didion)
 - *Study of Micro/Nano Scale EHD-Driven Flow Distribution Control and Heat Transfer Enhancement for Thermal Control Systems* NSTRF FY14 (Talmor & Yagoobi/WPI & Didion- NSTRF Mentor)
- **Flight Hardware: Electrically Driven Liquid Film Boiling**
 - ISS Fluids Rack – FY21





Technical Challenge: Component Thermal Management

Miniaturized, 3-D Electronics Packaging High Heat Flux Component Thermal Management

**3-D packaging Schema: Increase heat
generation and heat flux**

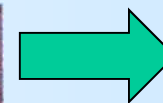
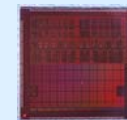
NASA Technology Infusion:

- System/Spacecraft on a chip (SoC)

- Stacked chip based components

- Embedded components on electronics board

- 3-D board packaging



Embedded SoC

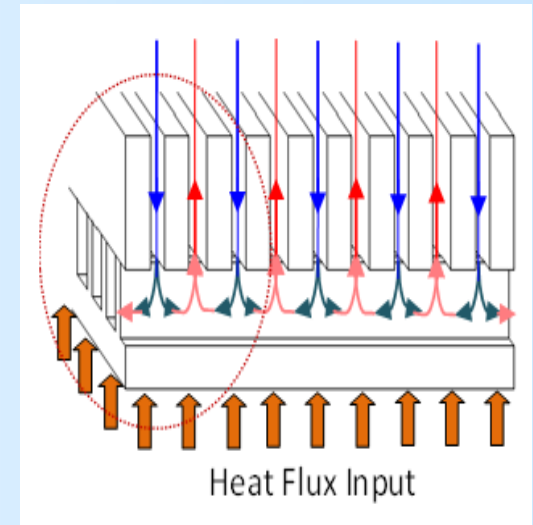


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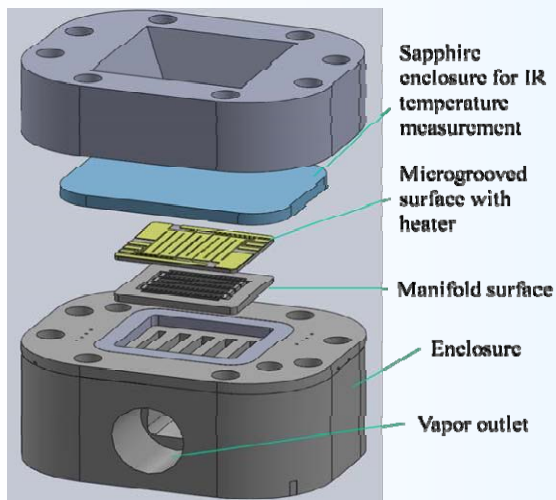
Technical Challenge: Component Thermal Management

- Chip Integrated Component: High Temperature Heat Acquisition & Transport
 - Thin Film evaporation for high heat acquisition rates @ low temperature difference
 - Hybrid EHD/Capillary Fluid Management
- Silicon Manifolds Operations
 - Liquid (blue) to heat acquisition site
 - Vapor (red) transported to heat rejection site
 - Manifold channels ~ 100 microns (gravity independence & micro-scale applications)
 - Electrohydrodynamic enhanced: alleviate dry-out; insure gravity insensitivity
- Technologies to Enable the Concept
 - Capillary driven flow: self regulation of mass flow rate
 - Electrohydrodynamics (EHD): fluid management (liquid/vapor control), pump enhancement
 - DRIE to manufacture micro-channels
- Feasibility
 - Micro-scale capillary performance demonstrated
 - EHD micro-scale microgravity fluid management in micro-gravity campaigns (May 2012 & September 2013)
 - Manufactured Proof-of-Concept micro-channel EHD electrode system
 - Manufactured Capillary Proof of Concept hardware





Component Heat Acquisition

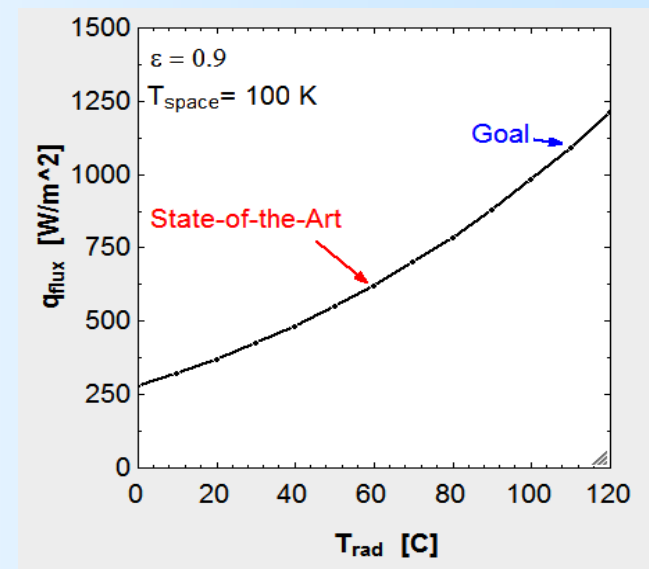


Hybrid Chip System Operation:

Heat Acquisition at Silicon Chip
Thin Film Evaporation
Electric Field Fluid Management
Heat Rejection @Lowest Temperature Sink

Radiator Size & Mass Advantage:

Higher Heat Rejection Temperature
Lower System Thermal Resistance

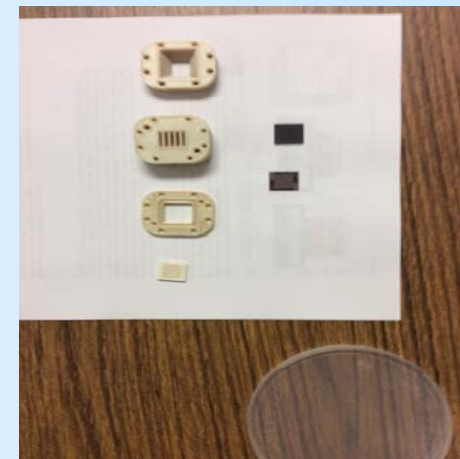




TechCube1: Component Heat Acquisition Proof of Concept

Component high heat flux embedded heat acquisition is high impact, unique technology enabling next generation of thermally limited, NASA and commercial computing, power and multifunctional platforms

- **CI-TMS is innovative and unique**
 - **Chip Embedded Hybrid EHD/capillary device provides high heat flux acquisition at heat source**
 - **Thin Film Evaporation and High Heat Rejection Temperature enable SWaP-C advantages**
- **Spaceflight Validation of Technology Concept on CubeSat Platform**



CI-TMS Proof of Concept Heat Acquisition Hardware





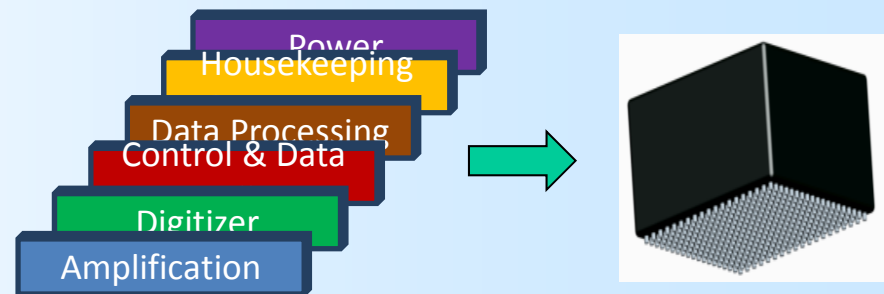
Technical Challenge: Multi-functional Structures

Embedded EHD Pumps

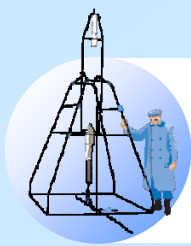
Electrical based: nano- to meso-scale phenomena

NASA Applications:

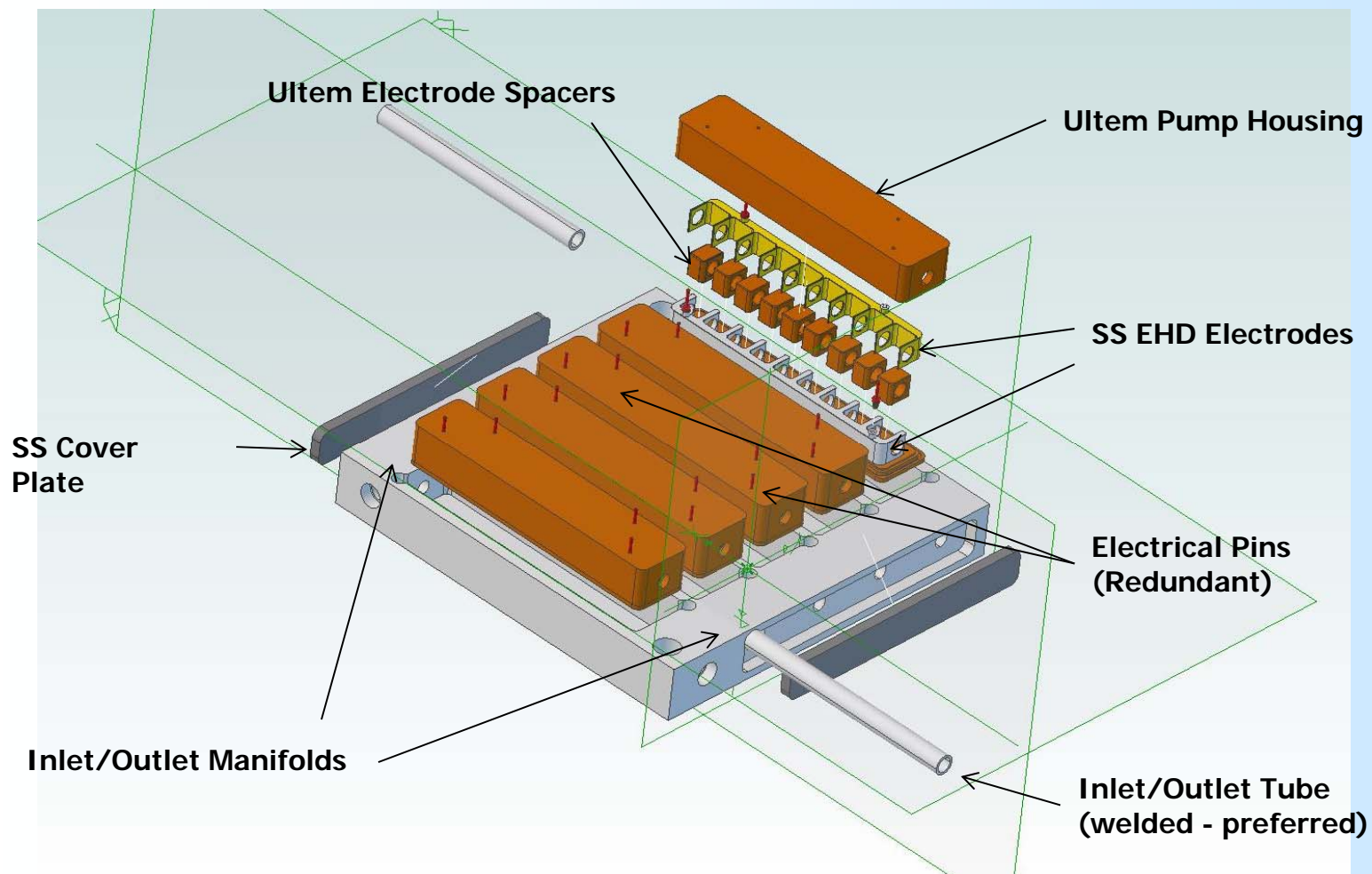
- Electronics board level
- Electronics Enclosures
- Structural-Thermal Plates
- Radiators



Electronics Bus



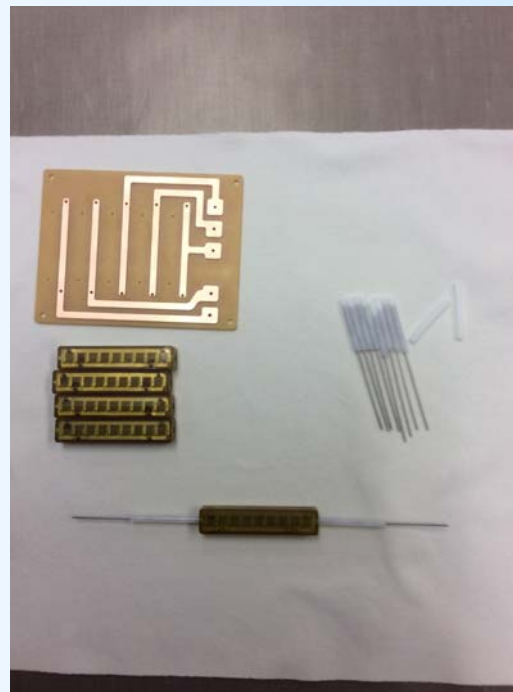
EHD Based Structural-Thermal Multifunctional Plate

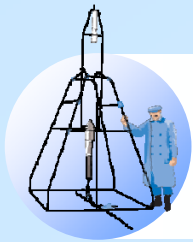




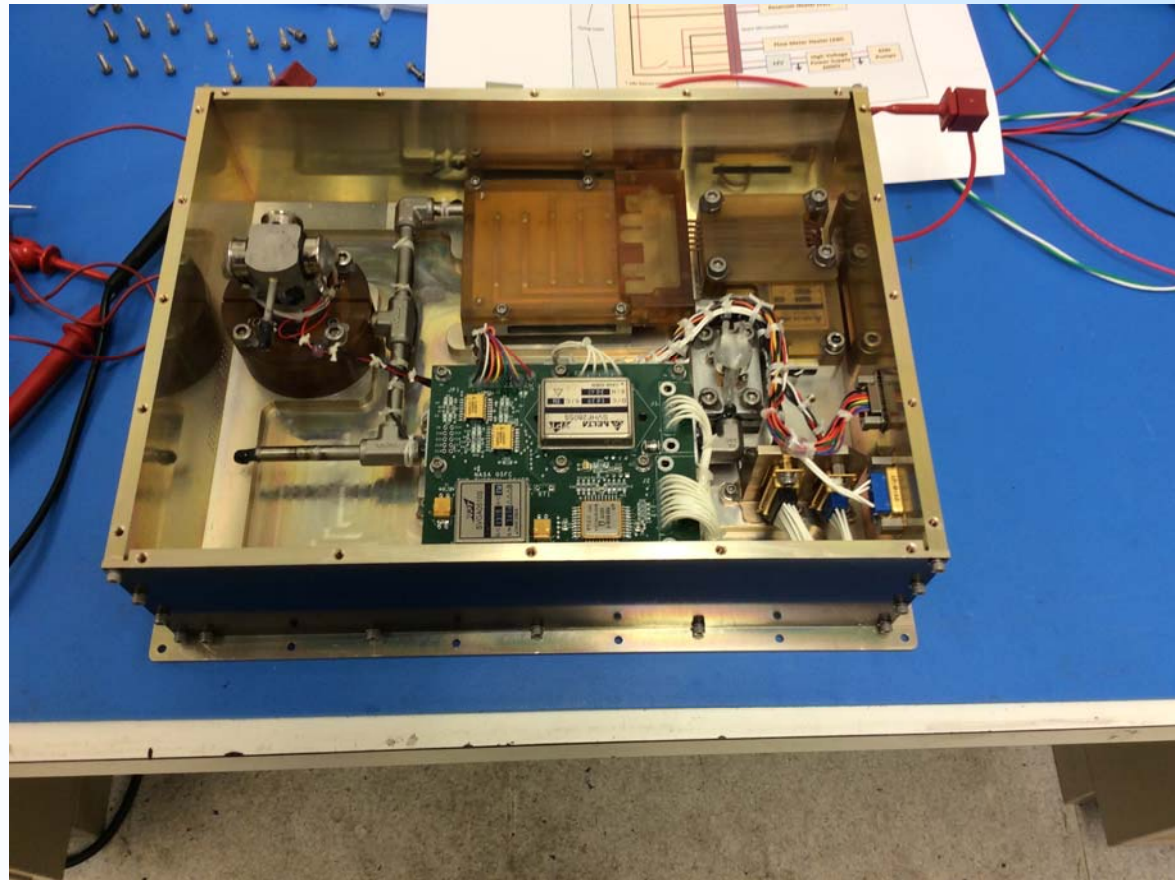
EHD Based Structural-Thermal Multifunctional Plate

- **Design & Fab EHD electrodes**
 - Electrode Fabrication: Hi Voltage & Ground
 - Smooth Sharp Edges
 - Insulate non-active surfaces
- **Integrate EHD electrodes**
 - Set into Ultem Container
 - Insert Ultem Spacers
 - Apply Epoxy/Closed out Pumps
- **Integrate into Multi-functional Plate**





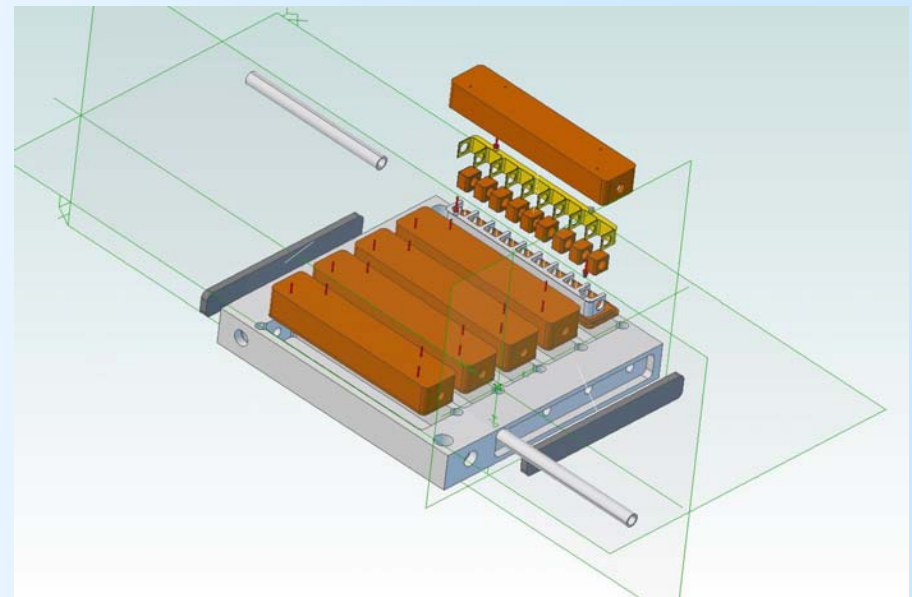
STP-H5: EHD Experiment Multifunctional Proof of Cooncept





Multi-Functional Plate: Next Generation Development Challenges

- **Simply Pump Design**
 - Eliminate spacers
 - Eliminate Ultem Housing
- **Power System**
 - Variable voltage power source (in progress)
 - Independent Pump Operations
 - Electric Bus Design
- **Additive Manufacturing**
- **Advanced Materials**
- **Smaller Pumps & Channels**





EHD Thin Film Boiling Experiment

Objective:

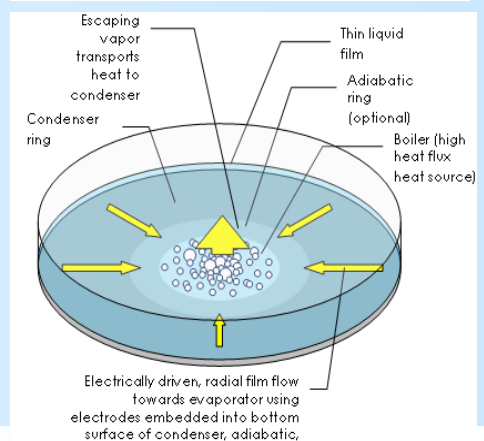
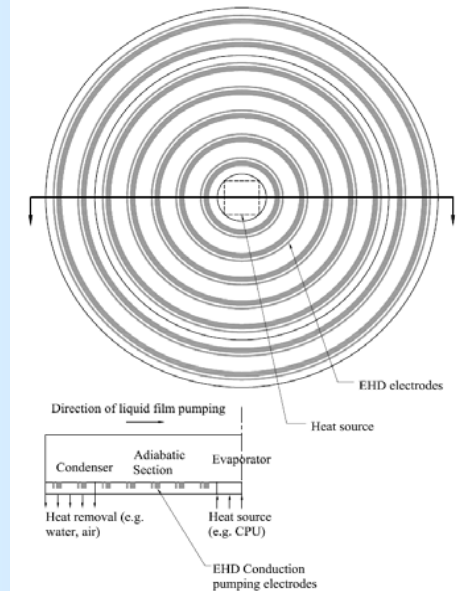
- ♦ Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to:
 - The effects of microgravity on the electrically generated two-phase flow.
 - The effects of microgravity on electrically driven liquid film boiling (includes extreme heat fluxes).
- ♦ Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.

Relevance/Impact:

- ♦ Provides phenomenological foundation for the development of electric field based two-phase thermal management systems leveraging EHD, permitting optimization of heat transfer surface area to volume ratios as well as achievement of high heat transfer coefficients thus resulting in system mass and volume savings.
- ♦ EHD replaces buoyancy or flow driven bubble removal from heated surface.

Development Approach:

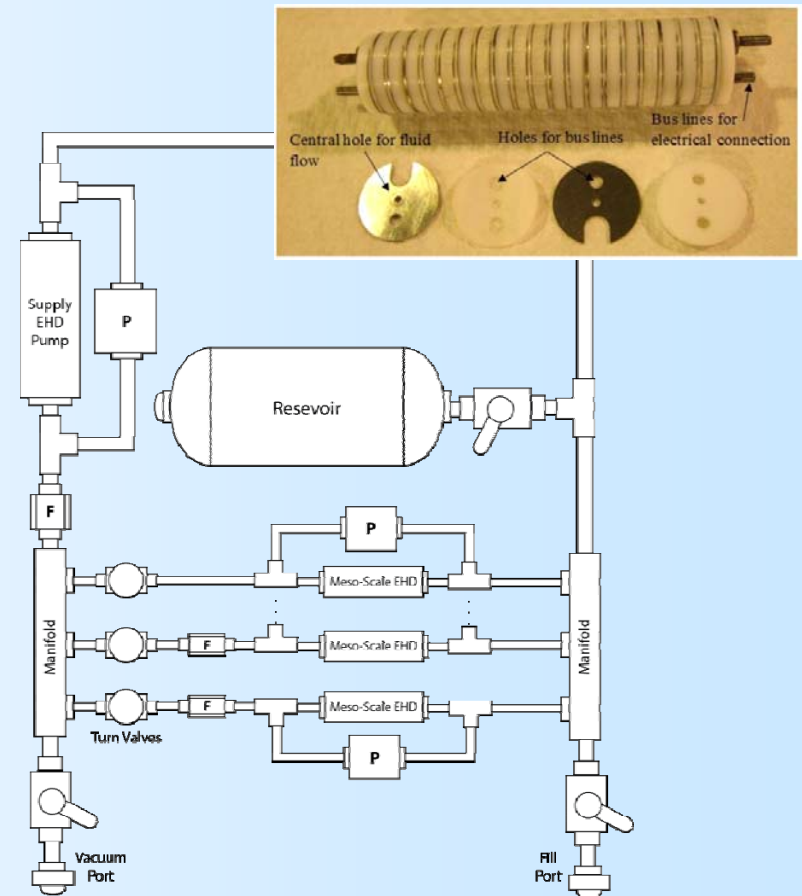
- ♦ Conduct preliminary experiments in low gravity and ground-based facilities to refine technique and obtain preliminary data for model development.
- ♦ ISS environment required to characterize electro-wetting effect on nucleate boiling and CHF in the absence of gravity.
- ♦ Will operate in the FIR – designed for autonomous operation.





Meso-Scale Flow Distribution (NSTRF)

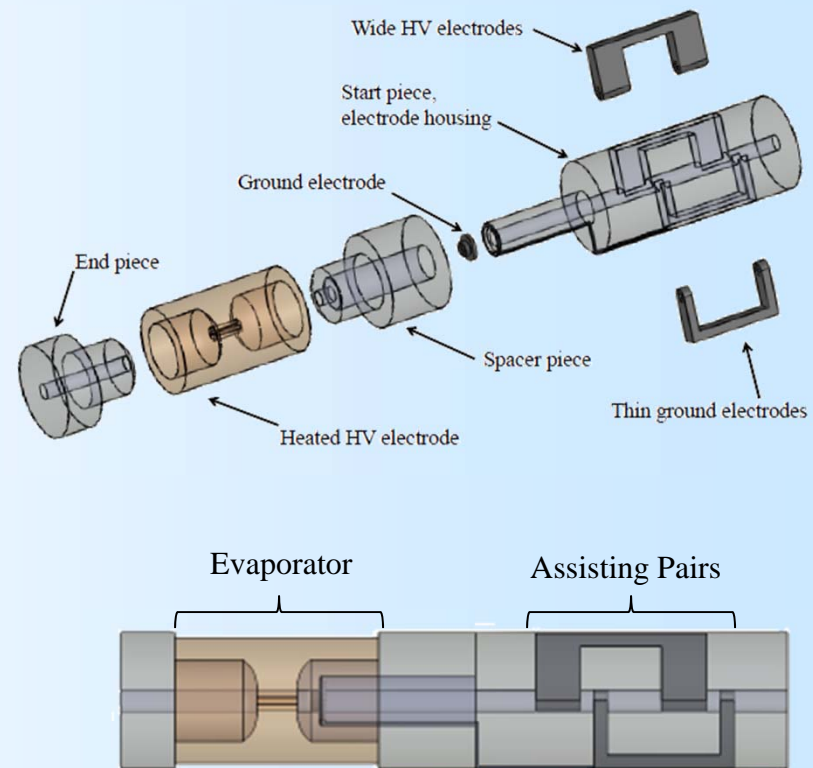
- Single and two-Phase flow
- Three parallel branches
- Entirely EHD driven
 - Branch embedded pumps
 - Flow supply pump
- Flow regime influence
- Flow distribution
 - Flow redirection
 - Maldistribution correction
 - Two-phase distribution stabilization





Micro-Scale EHD Enhanced Evaporation (NSTRF)

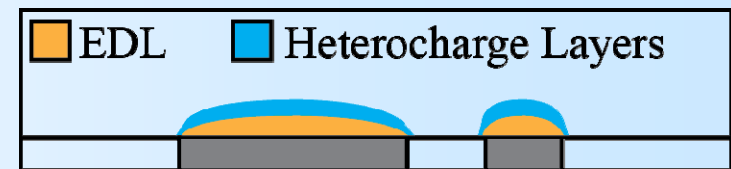
- Feasibility of embedded EHD enhancement
- Characterization of micro-scale perforations
 - Pressure generation
 - Flow rate generation
 - Flow regime estimate
 - Dry-out conditions
- Heat exchange loop
- Three electrode pairs
 - Two assisting upstream
 - One embedded in evaporator

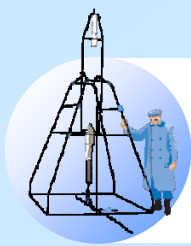




Nano-Scale Feasibility & Numerical Study (NSTRF)

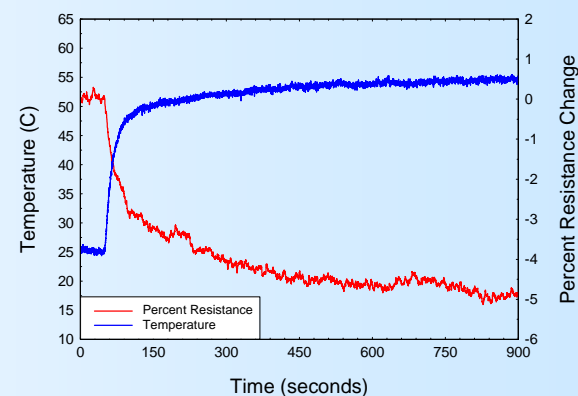
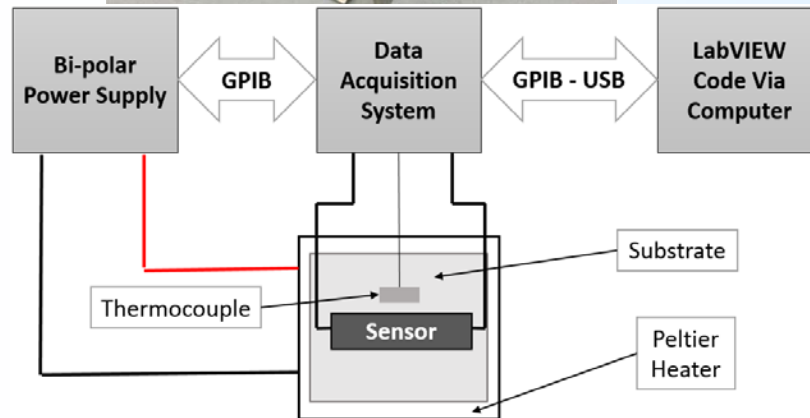
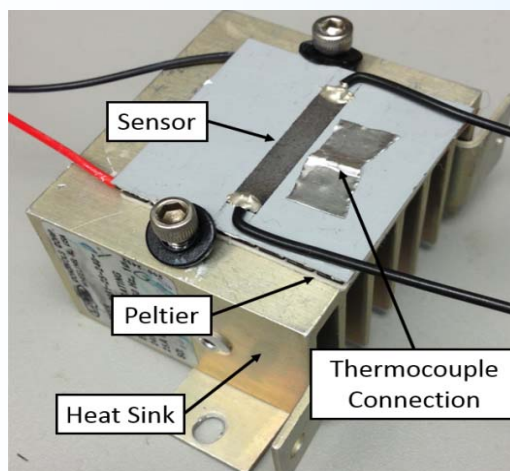
- Modeling & simulation:
 - Electric double layer vs. heterocharge layers
 - Significant effects from the zeta potential
 - Capillary and electrophoresis effects
 - Dimensions and materials revisit
- Experimentation:
 - Lithographic printing
 - Flow visualization
 - Single channel
 - Flow distribution



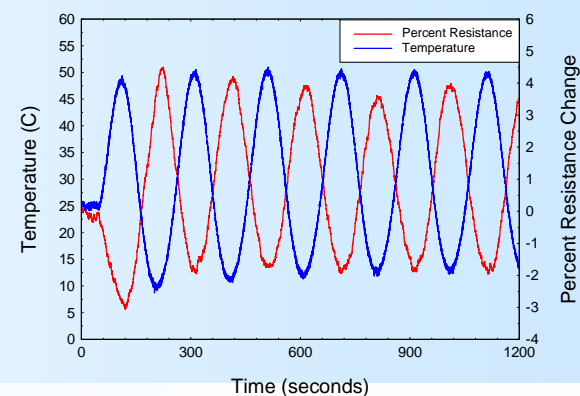


Self Sensing Thermal Management Using Nano-Enhanced Polymers

Multifunctional Nano-enhanced Structure acts as 'nervous system' to map temperature distribution



Temperature Step Function Response on Invar



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5 mHz Sine Wave Response on Invar